NRL Report 8285

Flashover Voltage of Some Electronegative Gases in Underwater Sound Transducers

L. P. BROWDER

Transducer Branch
Underwater Sound Reference Detachment
P.O. Box 8337
Orlando, Florida 32856

March 28, 1979

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Report 8285	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FLASHOVER VOLTAGE OF SOME ELECTRONEGATIVE GASES IN UNDERWATER SOUND TRANSDUCERS		5. TYPE OF REPORT & PERIOD COVERED Final report on one phase of the problem 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) L. P. Browder		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Underwater Sound Reference Detachment Naval Research Laboratory P.O. Box 8337, Orlando, FL 32856		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Problem S02-43 Program Element 64503N
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE March 28, 1979 13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Flashover voltage	Sulfur Hexaflouride
Sonar transducers	Air mixtures
Electrical breakdown	Water vapor in air
Electronegative gas	Chemical breakdown products
Perfluorocarbon gas	Empirical equations

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The flashover voltage of PZT ceramic in nitrogen and in several electronegative gases, especially sulfur hexafluoride and the perfluorocarbons, was tested. The results are related to electrical breakdown in sonar transducers. Empirical equations are presented for computing the flashover voltage of these gases and air mixtures with these gases as functions of pressure and distance. The effects of water vapor in air on the flashover voltage of ceramic are reported. The chemical breakdown products of the gases caused by moderate arcing are described.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

CONTENTS

FLASHOVER VOLTAGE OF SOME ELECTRONEGATIVE GASES IN UNDERWATER SOUND TRANSDUCERS

INTRODUCTION

The development and use of high-power sonar transducers by the U.S. Navy have introduced the need for high-voltage drive on the piezoelectric elements. Electrical discharge phenomena ranging from corona to arcing have been identified in transducers for several years, and a substantial percentage of failures have been traced to this effect. It is desirable to specify materials and design parameters that will allow use of the highest possible drive voltage with maximum reliability for the unit lifetime.

The weakest material in the transducer insulation system is the gaseous fill fluid. Common dry air or nitrogen are among the most economical of gases, so often they are the fill fluids used. Gases with better insulating properties than these are available, some with a substantial history of use in corona abatement applications. The final test of a material is always that of the performance in actual service. This report is concerned with evaluating the performance of some electronegative gases in sonar transducer service conditions.

Transducer Design Concerns

Sonar transducers have active elements of lead zirconate titanate (PZT) ceramic that is the main insulating barrier to the high-voltage drive. Figure 1 shows simplified drawings of 3,1 and 3,3 mode transducers and the flashover paths generally observed in service conditions. In this configurations the electrodes have sharp edges and the breakdown path is through the insulating gas on the surface of the PZT. This type breakdown is called surface flashover or "creepage," and in an otherwise well-designed transducer this may be the worst-case electrical failure mode.

Manuscript submitted September 30, 1978.

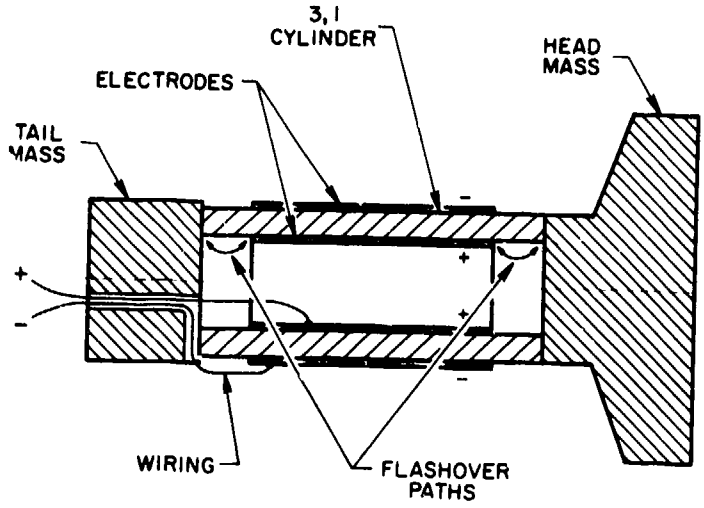

Fig. 1(a) — Surface flashover paths in 3,1 mode sonar transducers

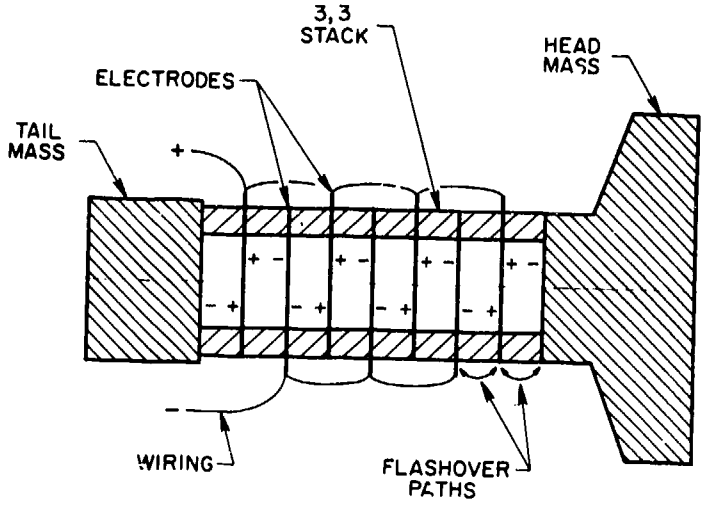

Fig. 1(b) — Surface flashover paths in 3,3 mode sonar transducers

Electrical Breakdown Concerns

Before specifying an insulating gas for a transducer fill fluid, some questions that must be answered about the characteristics of the gas are:

- What is the flashover breakdown voltage of the gas as a function of distance and pressure for the most corona-susceptible path?
- If we assume the gas will be contaminated by air and water vapor through permeation, how much safety margin must be provided?
- At what voltage does corona inception occur in the transducer filled with this gas?
- How much will corona discharges over a period of time degrade the insulating properties of the gas?

In addition to selecting a good insulating gas for the transducer, there are other factors that may be used to increase the safe operating level. These are:

- Increase gas pressure.
- Cover the ceramic and electrodes with a high dielectric strength coating.
- Use PZT ceramic having smooth surfaces.
- Avoid ragged edges on electrodes.
- Avoid surface contamination.
- Maintain the water vapor content of the gas to a low level.

BACKGROUND

Two important studies of the specific problems of corona in sonar transducers have been made in recent years. The first was in 1969 by Arthur D. Little Corp. [1], and the second was part of the MART series [2] in 1970. A major conclusion of these reports was that electronegative gases such as SF_6 and C_2F_6 would be advantageous replacements for nitrogen as a fill fluid in transducers. The data presented by these reports concerning the gases were mainly comparative and gave no realistic results to associate with transducer performance. Neither study identified surface flashover of PZT ceramic as a particular problem requiring analysis.

Other parts of the MART study proposed a mathematical modeling analysis of voltage breakdown considerations for transducers (MART 60, 73, and 121). The electric circuit analogy used for the model is a series assembly of dielectric materials between two plane electrodes that, unfortunately, is not the main failure mode. Because the surface flashover effect was not included in the calculations, the analysis indicated safe operating conditions in transducer areas that failed in practice. In addition, reasonable dielectric strength data for the gases in a uniform field were not used, and the analysis showed marginal breakdown conditions in safe areas, especially with shock transients. The analysis is good only where the conditions fit the electric circuit analogy and correct dielectric data are used.

MEASUREMENT METHOD

The voltage breakdown test for evaluating the insulator gases was designed to evaluate parameters directly experienced in sonar transducers. With these devices, voltage breakdown and corona occur in asymmetrical configurations with sharp electrode edges on PZT ceramic surfaces. The typical dielectric strength measurement of a gas is obtained with electrodes forming a uniform-field gap or a sphere gap. Some correlation is present between each of these methods, but the measurements of breakdown on the PZT surface are preferable for transducer design purposes.

Candidate Gas Selection

With the exception of nitrogen, the insulator gases chosen for these tests are all classified as electronegative. The molecules of electronegative gases capture free electrons in their outer shell forming singly charged negative ions. Other gases without this property are classified as free-electron. Air is an electronegative gas mixture due to the electron attaching action of the oxygen component. Most of these gases resist the formation of corona and have high dielectric strength.

The homologous series of gases with formulae C_nF_{2n+2} and C_nF_{2n} known as perfluorocarbons have strong molecular bonds and are electronegative. The chlorofluorocarbon gases $C\,Cl_2F_2$, $CH\,ClF_2$, $C\,ClF_3$, and C_2ClF_5 have weaker molecular bonds due to the chlorine atom; but they are listed as good dielectric gases [3] and have low boiling points. Selection of the perfluorocarbons for this series of evaluation tests was based on the molecular bond strength criteria.

The other gases tested were chosen because they are either presently in use or have been used in transducers. These include nitrogen (N_2), air, sulfur hexafluoride (SF_6), and carbon dioxide (CO_2). Sulfur hexafluoride has for many years been used by electrical industries as an insulator gas.

Test Setup

A block diagram of the test system is shown in Fig. 2. The high-voltage pulse for the flashover test was generated by a Velonex Model 360 high-power pulse unit. A high-voltage resistor was in series with the test sample to limit the arc current, and yet be small enough to appear as a low-impedance source. The flashover voltage across the ceramic surface was measured using a calibrated oscilloscope and a X1000 attenuator probe.

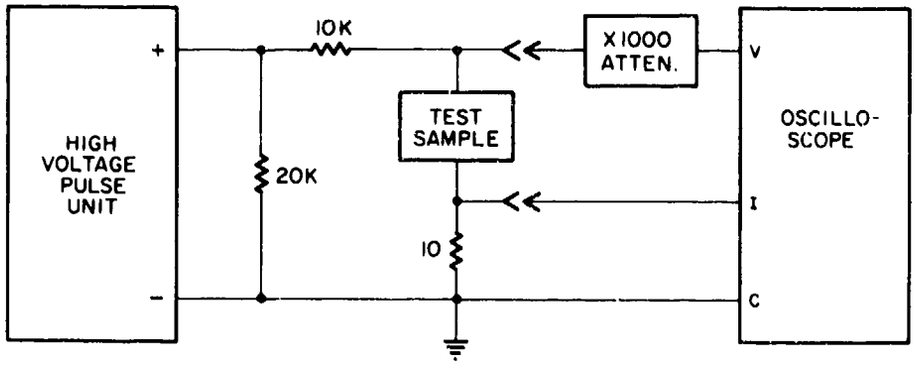

Fig. 2 — Block diagram of the electronic test system

The PZT-4 test sample was divided as shown in Fig. 3 so that sharp electrode edges were presented to the flashover gap. The test sample was mounted inside a small glass bell jar with access to the electrode leads provided by glass-to-metal seal connectors. The complete test cell is shown in Fig. 4.

Figure 5 is a diagram of the gas system. A vacuum was pulled in the system by a pump capable of an ultimate vacuum of 0.1 μm. Absolute pressure in the test chamber was monitored by a calibrated Wallace and Tiernan model FA160410 precision gage. Gas was injected into the system from the high-pressure tank via a gas regulator. Water vapor content was measured in each of the gases using Panametrics model 2000 electronic hygrometer with M22 probe. The drying agent used to remove water from air was anhydrous calcium sulfate (Drierite).

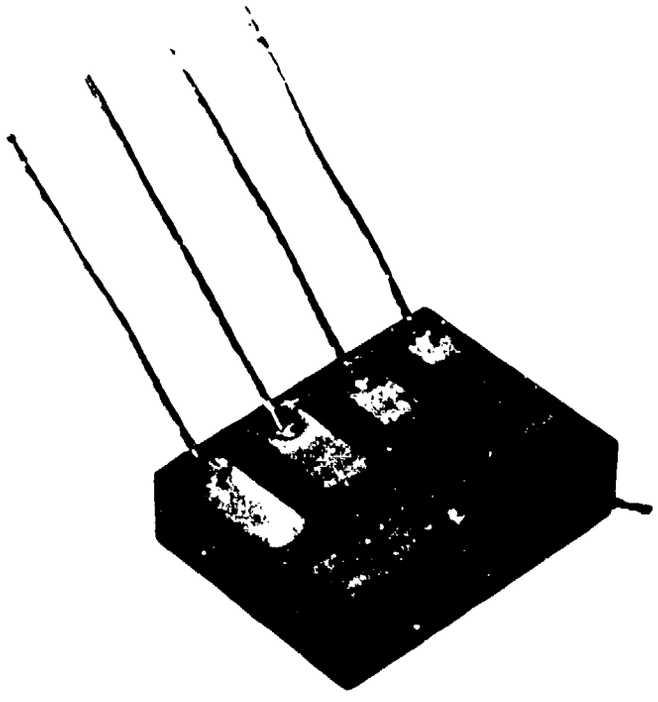

Fig. 3 — Surface flashover test sample

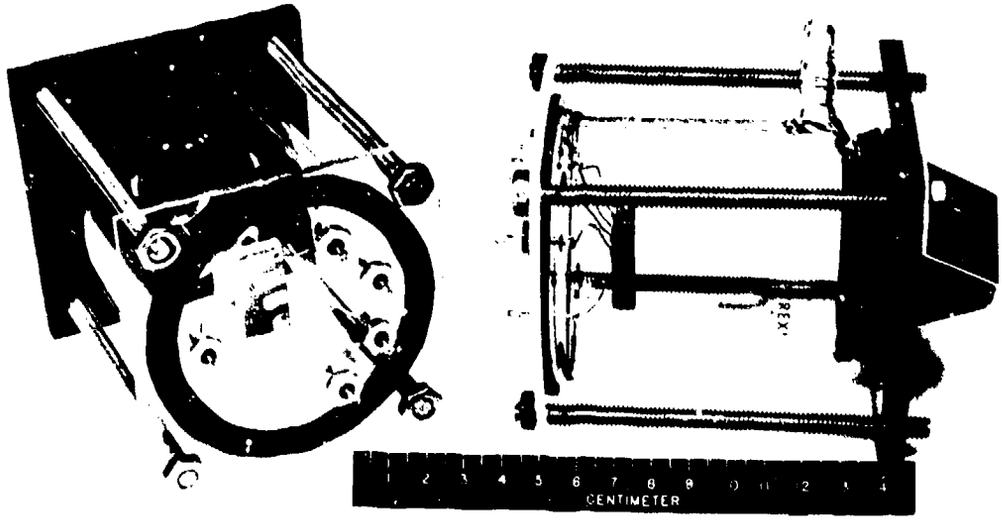

Fig. 4 — Gas test cell

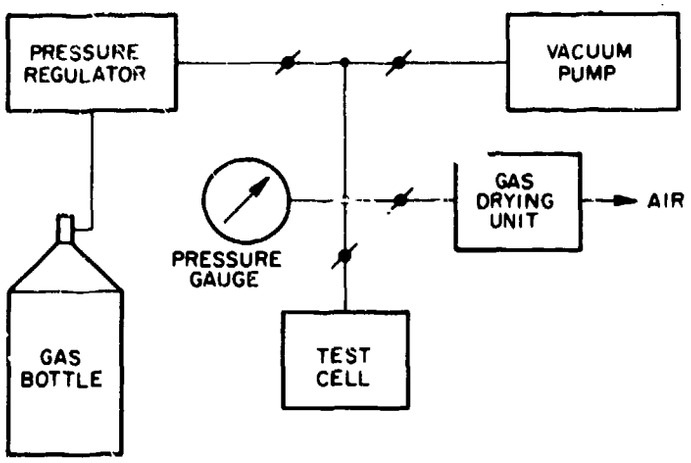

Fig. 5 — Block diagram of gas system

Measurement Description

The series of tests conducted on a candidate gas proceeded as follows:

1. Pull a vacuum on the gas system, including the test cell, for 15 minutes. Test to see that no vacuum leaks are present.
2. Alternately evacuate and flush the gas system two times with the test gas.
3. Introduce the test gas or gas mixture into the test cell to the correct pressure.
4. Seal the test cell and connect it to the high-voltage test unit.
5. Measure the surface flashover voltage for each electrode distance on the test sample.
6. Repeat steps 3 to 6 for each pressure and gas mixture required.
7. Fill the test cell with the test gas and proceed to visually examine the surface flashover phenomena using a telemicroscope.

Test Parameters

The tests were conducted using parameters with the same order of magnitude experienced in sonar transducers. The flashover distance between electrodes was in 2-mm steps from 2 to 8 mm total, and the absolute gas pressure range was from 35 to 138 kPa (59 to 20 psia). Separate tests established that the results obtained between 2 and 8 mm could be extrapolated to distances ranging from 1 to 13 mm.

The high-voltage pulse applied to the electrodes of the test sample was adjusted so that the flashover event was essentially nondestructive to the PZT ceramic. With a pulse duration of about 200 μs there was only a small indication of burning after 1000 pulses. A repetition rate of 1 pps was used, and the series resistor limited the arc current to a level of 0.3 to 1.5 A. The rise time of the pulse was 10 μs and would simulate the leading edge of an ac voltage drive with a frequency of 25 kHz.

The flashover voltage level (V_f) recorded was the average of about 10 events. This phenomenon does not give a stable indication for V_f, nor does the surface flashover event occur successively in the same path on the test sample. The overall instability of V_f is about ±10% with larger percentage variations for greater flashover distances.

MEASUREMENT RESULTS

The test results emphasize the basic similarity of the insulator gases when functions of flashover voltage (V_f) vs gap distance and gas pressure are compared. Also observed were fundamental differences between the flashover arc formation in the perfluorocarbons, sulfur hexafluoride, and air or nitrogen that have influence on the potential usefulness of the gases as insulators.

Flashover Arc Description

The flashover arc in air and nitrogen was slightly purple in color and adhered closely to the PZT surface. At voltage levels a little lower than flashover, small flashes of corona could be observed on the edges of the electrodes and around small bits and scratches on the surface. The flashover path was often associated with this surface corona. With continued heavy arcing on the test sample, preferred flashover locations develop and the PZT surface becomes darker in this area. Arcing always caused the sharp electrode edges to partially melt and roll up into a distorted shape.

With sulfur hexafluoride, the arc on the PZT surface was white and was joined by a flame-like halo corona extending outward about 0.5 mm. The formation was surrounded by ionized gas. Multiple arc paths sometimes formed during a single voltage pulse. A relatively large amount of corona activity was observed on the positive electrode edge that caused ceramic and electrode erosion.

Flashover in the perfluorocarbon gases was an intense white plasma channel that moved outward from the ceramic surface. A weak arc was sometimes observed on the surface that paralleled the plasma channel, but its action produced only minor ceramic erosion.

Flashover Voltage of Gases

A typical family of curves showing the function of V_f with flashover distance and gas pressure is shown in Fig. 6. About 50% of the flashover events occurred at the recorded levels; the max/min variation of V_f was approximately ±10%. Therefore, surface flashover may occur at a level 10% lower than indicated. Also, the V_f level is peak voltage and must be multiplied by $1/\sqrt{2}$ to obtain the equivalent ac rms value. Tables 1 through 10 show data for each of the candidate gases. The primary usefulness of these results is to provide a working comparison between the gases in a transducer environment. Nitrogen is the weakest gas tested, V_f being about 0.8 that for air. CO_2 and CF_4 have V_f's relatively the same and about 1.25 that for air. These tests *do not* constitute an endorsement for the use of CO_2 in transducers; there have been permeation problems reported with its use. SF_6 and the other perfluorocarbon gases tested all have substantially higher relative flashover voltage levels as compared to air.

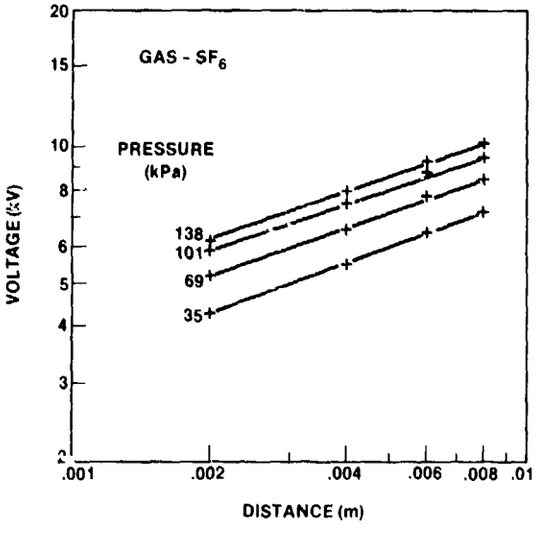

Fig. 6 — Flashover voltage of SF_6

Table 1 — Nitrogen (N_2)

Gap Distance (m)	Pressure — kPa (psia)			
	35 (5)	69 (10)	101 (14.7)	138 (20)
	V_f (kV)	V_f (kV)	V_f (kV)	V_f (kV)
.002	2.3	2.5	2.8	3.0
.004	3.1	3.3	3.5	3.7
.006	3.6	3.9	4.2	4.3
.008	4.0	4.3	4.5	4.8

Table 2 — Air (N_2 + O_2)

Gap Distance (m)	Pressure — kPa (psia)			
	35 (5)	69 (10)	101 (14.7)	138 (20)
	V_f (kV)	V_f (kV)	V_f (kV)	V_f (kV)
.002	2.4	2.9	3.2	3.3
.004	3.2	3.9	4.5	4.8
.006	3.9	4.8	5.6	5.8
.008	4.7	5.6	6.3	6.8

Table 3 — Carbon Dioxide (CO_2)

Gap Distance (m)	Pressure — kPa (psia)			
	35 (5)	69 (10)	101 (14.7)	138 (20)
	V_f (kV)	V_f (kV)	V_f (kV)	V_f (kV)
.002	3.0	3.7	4.3	4.8
.004	4.0	4.9	5.8	6.4
.006	4.7	5.9	6.6	7.5
.008	5.5	6.5	7.5	8.5

Table 4 — Sulfur Hexafluoride (SF_6)

Gap Distance (m)	Pressure — kPa (psia)			
	35 (5)	69 (10)	101 (14.7)	138 (20)
	V_f (kV)	V_f (kV)	V_f (kV)	V_f (kV)
.002	4.3	5.2	5.9	6.2
.004	5.5	6.6	7.5	8.0
.006	6.5	7.8	8.8	9.3
.008	7.2	8.5	9.5	10.2

Table 5 — Perfluoromethane (CF_4)

Gap Distance (m)	Pressure — kPa (psia)			
	35 (5)	69 (10)	101 (14.7)	138 (20)
	V_f (kV)	V_f (kV)	V_f (kV)	V_f (kV)
.002	3.0	3.9	4.5	4.7
.004	4.1	5.0	6.0	6.5
.006	4.7	5.8	7.0	7.3
.008	5.6	6.7	7.9	8.1

Table 6 — Perfluoroethane (C_2F_6)

Gap Distance (m)	Pressure — kPa (psia)			
	35 (5)	69 (10)	101 (14.7)	138 (20)
	V_f (kV)	V_f (kV)	V_f (kV)	V_f (kV)
.002	4.3	5.2	5.8	6.4
.004	6.0	7.2	7.9	8.6
.006	7.3	8.5	9.4	10.3
.008	8.4	9.6	10.5	11.4

Table 7 — Perfluoropropane (C_3F_8)

Gap Distance (m)	Pressure — kPa (psia)			
	35 (5)	69 (10)	101 (14.7)	138 (20)
	V_f (kV)	V_f (kV)	V_f (kV)	V_f (kV)
.002	4.9	6.2	7.2	8.2
.004	6.5	7.8	9.0	10.0
.006	7.2	8.8	10.0	11.2
.008	8.2	9.9	11.5	13.0

Table 8 — Perfluorocyclobutane (C_4F_8)

Gap Distance (m)	Pressure — kPa (psia)			
	35 (5)	69 (10)	101 (14.7)	138 (20)
	V_f (kV)	V_f (kV)	V_f (kV)	V_f (kV)
.002	5.2	6.0	6.4	7.0
.004	6.6	8.0	8.5	9.5
.006	7.0	9.2	10.1	11.0
.008	9.0	10.8	11.5	12.0

Table 9 — Perfluorobutane (C_4F_{10})

Gap Distance (m)	Pressure — kPa (psia)			
	35 (5)	69 (10)	101 (14.7)	138 (20)
	V_f (kV)	V_f (kV)	V_f (kV)	V_f (kV)
.002	5.2	6.5	7.0	8.0
.004	7.2	9.0	10.2	11.0
.006	9.0	11.0	12.2	13.0
.008	10.5	12.5	14.0	14.5

Table 10 — Perfluoroisobutane $(CF_3)_3$ CF

Gap Distance (m)	Pressure — kPa (psia)			
	35 (5)	69 (10)	101 (14.7)	138 (20)
	V_f (kV)	V_f (kV)	V_f (kV)	V_f (kV)
.002	5.5	6.5	7.0	7.3
.004	6.8	7.8	9.0	9.4
.006	7.6	8.8	10.0	10.8
.008	8.5	10.2	11.0	11.8

Analysis of the data from the ten gases indicated that the flashover voltage function could be expressed by the empirical equation

$$V_f = K d^n p^m \tag{1}$$

where V_f is a flashover voltage in kilovolts, d is gap distance in meters, and p is gas pressure in kilopascals. Constants K, n, and m are factors determined from the data. The following equations apply to the gases indicated.

Nitrogen (N_2) $V_f = 13.7\, d^{.36} p^{.14}$ (2)

Air ($N_2 + O_2$) $V_f = 22.1\, d^{.50} p^{.25}$ (3)

Carbon Dioxide (CO_2) $V_f = 11.5\, d^{.41} p^{.34}$ (4)

Sulfur Hexafluoride (SF_6) $V_f = 16\, d^{.35} p^{.25}$ (5)

Perfluoromethane (CF_4) $V_f = 12.4\, d^{.40} p^{.31}$ (6)

Perfluoroethane (C_2F_6) $V_f = 25.2\, d^{.42} p^{.25}$ (7)

Perfluoropropane (C_3F_8) $V_f = 11.7\, d^{.33} p^{.34}$ (8)

Perfluorocyclobutane (C_4F_8) $V_f = 30.3\, d^{.43} p^{.24}$ (9)

Perfluorobutane (C_4F_{10}) $V_f = 36.1\, d^{.46} p^{.27}$ (10)

Perfluoroisobutane $(CF_3)_3$ CF $V_f = 18.4\, d^{.33} p^{.23}$ (11)

These functions apply for gap distances from 0.001 to 0.013 m and pressures from 35 to 138 kPa absolute.

From the generally reported data for the voltage breakdown (V_B) of air in a uniform field [4], the equation

$$V_B = 30.5\, d^{.84} p^{.84} \tag{12}$$

may be obtained. Equations (3) and (12) apply only to air, but with different electrode and surface configurations. Transducers may have configurations that range from the uniform field to the surface flashover condition. Numerical comparison of these equations at atmospheric pressure shows that the uniform field breakdown voltage can be from 2 to 5 times greater than the surface flashover voltage; therefore, the inappropriate use of Eq. (12) will indicate a margin of safety where none exists.

Gas-Air Mixtures

Flashover voltage of the electronegative gases mixed with dry air was measured to determine if this would cause any significant quality-control problem. In transducers, gas mixture could be caused by faulty filling procedures, system leaks, or gas permeation. Figures 7 and 8 show effects on the flashover voltage of air mixed with SF_6 and C_2F_6, respectively. Air mixed with the other gases gave similar results. The insulating properties of these gases do not change appreciably when contaminated with small quantities of air.

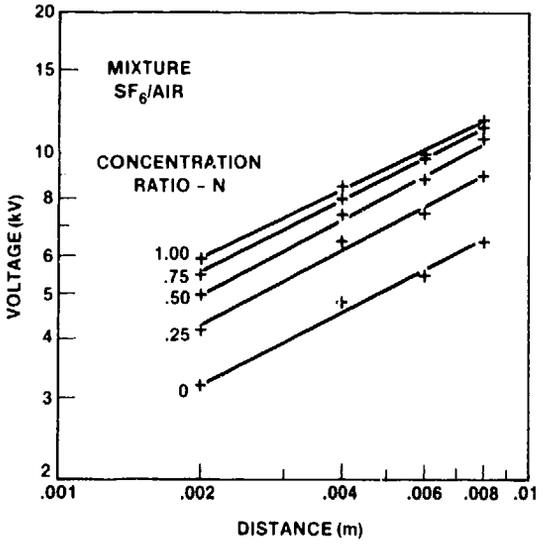

Fig. 7 — Flashover voltage of SF_6 and air mixtures

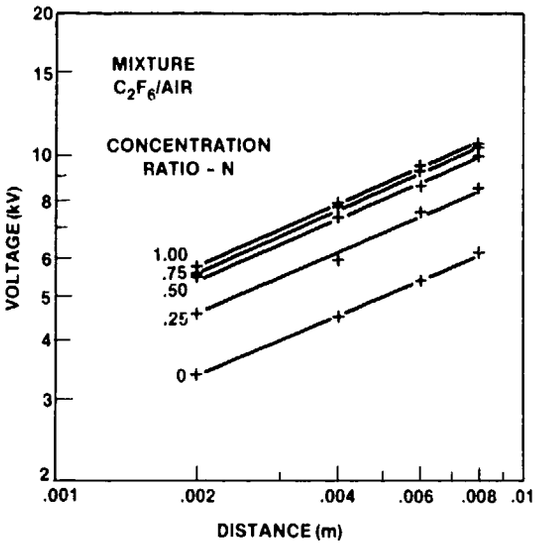

Fig. 8 — Flashover voltage of C_2F_6 and air mixtures

Evaluation of the data obtained for V_f with mixtures of these gases and dry air indicated the empirical equation

$$V_f(\text{mixture}) = V_{f1} + N^s (V_{f2} - V_{f1}) \tag{13}$$

where V_{f1} is the flashover voltage of air from Eq. (3), and V_{f2} is for the stronger gases from Eqs. (4) through (11). N is the partial pressure concentration ratio of insulating gas in the air mixture. The value of the exponent s is not clearly assessed by the experimental data but approximate numbers are 0.5 for C_2F_6; 0.65 for SF_6, C_3F_3, C_4F_{10}, and CO_2; and 1.0 for CF_4, C_4F_8, and $(CF_3)_3$ CF.

Figure 9 shows a typical application of Eq. (13). This evaluates surface flashover voltage in TR155 transducers with changing gas concentration ratios of SF_6 in air. Various typical gas pressures (absolute) are used, and the gap distance is .0127 m (500 mils). V_f is computed as kV rms, and a 10% safety margin is included.

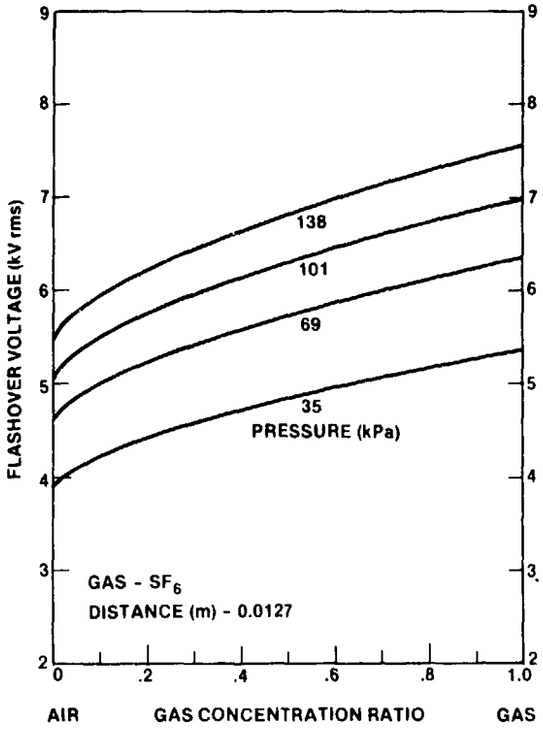

Fig. 9 — Computed flashover voltage of SF_6 and air mixtures for TR155 transducers

Air-Water Vapor Mixtures

The effect on the flashover voltage of air and water vapor mixtures was tested. The tests were at a temperature of 25°C with relative humidity (RH) from approximately 0.005 to 96%. An RH of 96% corresponds to about 3% water-vapor content in the air by partial pressure. The general indication with increasing RH was a small increase of flashover voltage, perhaps 10 to 20%. Most of this change occurred with RH between 0.005 and 25%. Similar reports of this effect have been made [4,5].

A good practice is to limit the maximum water-vapor partial pressure in sonar transducers to about 4.6 mmHg or the equivalent relative humidity of 20% at 25°C. The difficulty with water vapor in an insulation system is that a water film forms on the insulating surfaces. This causes adverse effects including surface tracking, silver migration, hydrolysis, and water treeing. Surface tracking is the result of surface sparks generated by water-film evaporation that breaks a leakage current path [6,7]. All of the adverse effects are associated with a high relative humidity.

Gas Breakdown Products

Tests were conducted to determine the effect of moderate amounts of arcing on the insulator gases. The test duration for each gas was 30 minutes with 10 pps, 200 μs per pulse with an arc current of 1 A. This test was sufficiently severe so that there was some removal of the silver electrode material, and burning or erosion of the PZT ceramic occurred. A transducer that was affected this much by electrical breakdown could be easily identified by visual inspection of the ceramic.

Arcing in the perfluorocarbon gases caused a brownish solid deposit resembling lampblack to form on the cooler parts of the ceramic. This is believed to be some form of carbon precipitate. The deposit was heaviest with C_4F_8; medium with C_4F_{10} and $(CF_3)_3CF$; and light with CF_4, C_2F_6, and C_3F_8. There was no evidence of etching of the glass test cell to indicate the presence of fluorine gas.

Arcing in sulfur hexafluoride gas produced an odor indicating the presence of small quantities of sulfur dioxide (SO_2) and hydrogen sulfide (H_2S). Fluorine gas may have been liberated because there was some etching of the glass cell. A very small quantity of a whitish solid precipitate that could have been some form of sulfur was observed. As the positive electrode was eroded by the arc, a black deposit was left that may have been silver sulfide (Ag_2S).

There was no evidence that the flashover voltage of the test gases changed during the test. The observed changes were associated with deterioration of the electrodes and PZT surface. This result is consistent with other observations that small amounts of gaseous contamination in a strong insulator gas produces minor changes in the insulating properties; conversely, small amounts of a strong insulator gas in one that is weaker produces improvements substantially greater than the linear ratio indicates.

RELATIVE GAS RATINGS

Table 11 summarizes some of the results of this study and is a general indicator of the best insulator gases. Sulfur hexafluoride, SF_6, is a good choice and is considerably better than air or nitrogen. Three others, C_2F_6, C_3F_8, and C_4F_{10}, are equally good or superior to SF_6 and are recommended for use in transducers. However, C_4F_{10} and C_3F_8 have higher boiling points than the aforesaid, −2 and −36.7°C, respectively. This could make them unsuitable for pressurized transducers or for storage or operation in a cold environment.

Table 11 — Insulator Gas Comparisons

Gas Name	Chemical Formula	Boiling Point (°C)	Flashover Voltage Relative to Air d = .006 m	Dielectric Strength Across PZT @ 0.0127 m and 101 kPa kV/m (V/mil)	Dielectric Strength Retention in Air Mixtures	Chemical Stability in Arc
Nitrogen	N_2	−195.8	.8	295 (7.5)	—	—
Air	$N_2 + O_2$	−183 (O_2)	1.0	445 (11.3)	—	—
Carbon Dioxide	CO_2	− 80	1.2	500 (12.8)	med.	—
Sulfur Hexafluoride	SF_6	− 63.8	1.6	620 (15.8)	med.	med.
Perfluoromethane	CF_4	−128	1.2	530 (13.4)	poor	good
Perfluoroethane	C_2F_6	− 78.2	1.7	715 (18.2)	good	good
Perfluoropropane	C_3F_8	− 36.7	1.9	770 (19.6)	med.	good
Perfluorocyclobutane	C_4F_8	− 5.8	1.9	795 (20.2)	poor	poor
Perfluorobutane	C_4F_{10}	− 2.0	2.2	940 (23.8)	med.	med.
Perfluoroisobutane	$(CF_3)_3$ CF	− 2.0	1.8	760 (19.3)	poor	med.

CONCLUSIONS

- Results have been obtained that establish that several electronegative gases (SF_6, C_2F_6, C_3F_8, and C_4F_{10}) are superior to nitrogen and air as insulating fill fluids for sonar transducers.

- Equations are presented for computing flashover voltage over PZT ceramic in the various gases and with air mixtures of these gases.

- The flashover voltage over the PZT ceramic is substantially lower than the breakdown voltage of a uniform field with the same insulator gas, gap distance, and gas pressure.

- A small amount of air contamination does not seriously degrade the insulating properties of these electronegative gases.

- Limited values of corona discharge and flashover have little effect on the flashover voltage of the insulator gas.

- Water vapor appears to increase the flashover voltage of air by a small amount.

• Sulfur hexafluoride (SF_6) seems to allow the formation of corona more readily than do the perfluorocarbon gases.

REFERENCES

1. "Failure Analysis of TR155," Arthur D. Little Corp., Contract N00024-69-C-1240, (1969).
2. R.S. Evans, "Applicability of Existing Technology for Corona and Arc-over Control to Transducer Elements," MART F2; Task No. 3.1.1.1.9.1; Electric Boat Division; (May 22, 1970).
3. H.L. Saums and W.W. Pendleton, *Materials for Electrical Insulating and Dielectric Functions*, Hayden, N.J., pp. 313-315 (1973).
4. E. Kuffel and M. Abdullah, *High-Voltage Engineering*, Pergamon Press, Oxford, pp. 198-238 (1970).
5. L.R. Loeb, *Electrical Coronas Their Basic Physical Mechanisms*, University of California Press, Berkeley and Los Angeles, pp. 225-227 (1965).
6. L.L. Alston, *High-Voltage Technology*, Oxford University Press, London, pp. 158-166 (1968).
7. American Society for Testing and Materials, *1978 Annual Book of ASTM Standards*, Part 39, Standard Method of Test for Liquid-Contaminent, Inclined-Plane Tracking and Erosion of Insulating Materials, ASTM Designation D2303-73.